How many juvenile abalone are there?
The example of *Haliotis roei*

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Abstract

We use population surveys of *Haliotis roei* on intertidal rock platforms at Perth, Western Australia to examine recruitment of juvenile individuals into the adult, fishable population. Despite intensive surveys conducted seasonally and over several years very few small *H. roei* were found. We propose the following life cycle for *Haliotis roei*: juveniles grow fast, reach adult size quickly, and survive for a number of years as adults. Recruitment of juveniles to the adult population is low, either through a steady annual maturation of juveniles or by substantial recruitment during an occasional good year.

Introduction

A number of the larger species of abalone (genus *Haliotis*) combine to form one of the most commercially important groups of molluscs in the world. Abalone have attracted considerable research interest, and two major recent symposia were devoted entirely to the group (Shepherd *et al.* 1992; Shepherd *et al.* 1995).

Very high levels of exploitation have caused the collapse of a number of major abalone fisheries, including those in California (Tegner *et al.* 1992; Parker *et al.* 1992) and Mexico (Guzman del Proo 1992). Understanding the reasons for the collapse of abalone populations supporting wild fisheries is essential for the sustainable management of the remaining commercially fished populations. In this paper we argue that recruitment of juvenile abalone into a population may be substantially lower than currently thought, thus increasing the chance of recruitment failure.

Size structure in surveyed populations of some abalone species is typically skewed to the right with a preponderance of accumulated year classes and very few juveniles (Tegner *et al.* 1992; Wells and Keesing 1989; 1990; Wells and Mulvay 1995). It is frequently assumed that the lack of juveniles found in surveys is a sampling artefact caused by the inability of researchers to effectively sample juveniles in cryptic habitats. There is an alternative possibility: that juveniles are not abundant but grow fast, quickly reach adult size, and survive for many years as adults. Recruitment of juveniles to

the adult population may thus be low, and heavily dependent on levels of natural mortality, known to be high. If this is true, fished populations will be largely based on occasional years when recruitment is high. Fisheries with these characteristics are susceptible to growth overfishing.

The present paper examines available information for *Haliotis roei* Gray to examine whether the rate of recruitment of juveniles to the fishable population is characterised by low levels of steady recruitment or high interannual variability. Juveniles of *H. roei* are relatively easily sampled on intertidal limestone platforms in the Perth area as there are few places for them to hide and the growth characteristics are well known (Keesing and Wells 1989).

Materials and methods

In the Perth metropolitan area of Western Australia *H. roei* is abundant near the seaward margin of intertidal limestone platforms. The platforms studied are flat at about low tide level and extend seaward for up to 100 m from the shoreline. The platform margin may be raised a few centimetres, trapping water on the platform during low tide. At the seaward margin the platform drops vertically before reaching the bottom of sand or rock at a depth of several metres; the vertical dropoff may be undercut. Few, if any loose rocks occur on the platforms. The surface is irregular, with holes several centimetres across and deep on the entire surface. In some areas near the platform margin solution pipes may penetrate through the platform to the undersurfaces. Crustose coralline algae occur only near the seaward margin of the platform. Grazing molluscs, particularly limpets, keep many parts of the platform surface near the margin largely free of macroalgae (Scheibling *et al.* 1990). The subtidal vertical cliff at the seaward margin of the platform is relatively smooth. Thus there are few hiding places for small abalone.

Data collected from two platforms are examined here. Waterman has been a fishery reserve since the late 1960s and has not been subjected to fishing. In contrast, the platform 3 km to the south at Trigg has been extensively fished over many years, originally by professional then later by recreational fishers. The platforms have a clear habitat zonation (see Wells and Keesing, 1986): the inshore platform has a variety of macroalgae in summer which are removed by winter wave action; the *Sargassum* zone with large macroalgae which persist during winter; and a bare zone near the seaward margin of the platform where few macroalgae are present.

Detailed sampling of all molluscs present was undertaken in January of each year from 1983 to 1986. In each habitat a transect of 8 stations 5–10 m apart was sampled. At each station all molluscs 5 mm or more in shell length (SL) counted and as far as possible identified in the field. Abalone spawn in the winter months of July and August, and reach a shell length of 46 mm after one year. Individuals < 20 mm SL sampled in January would thus be 0+ animals spawned during the previous winter.

Two surveys were undertaken to measure the small scale distribution of abalone. To examine horizontal distribution of abalone on the platform, 6 transects were made perpendicular to the seaward edge of the platform at Trigg. The transects were 10 m long and stretched from the seaward edge of the platform into the *Sargassum* zone. Every metre a 50 x 50 cm quadrat was examined and all abalone counted and measured in situ with callipers. A second quadrat, adjacent to the first, was subdivided into a grid and used to estimate the cover of crustose coralline algae.

A site on the cliff face at the seaward edge of the platform at Waterman was used to measure vertical distribution of *H. roei* on the seaward subtidal cliff. Five transects were run from the top of the platform, at about the low tide line, to the bottom at a depth of about 1.8 m. Quadrats were 50 cm wide and 30 cm high.

Size frequency measurements were made quarterly from January 1983 to January 1985 at 2 sites in the bare zone at Waterman and 3 sites at Trigg. A 50 x 50 cm quadrat was placed in the bare zone and all abalone measured to the nearest millimetre with callipers. A total of 20 quadrats were haphazardly sampled at each site. Because of the exposed position of the sites, some quarters were missed at some sites during the winter.

To examine repopulation of abalone from a denuded reef, all abalone were removed from a subtidal rock approximately 2 m in diameter and extending 1.8 m from the sand bottom to the surface in the Waterman reserve in March 1983. All abalone visible were removed daily for a period of 5 days. The number of abalone collected declined rapidly after the first day, with fewer than 20 animals collected on the last day. Visual observations were also made in November 1983 and March 1984. The rock was cleared again in March 1985 and 1987.
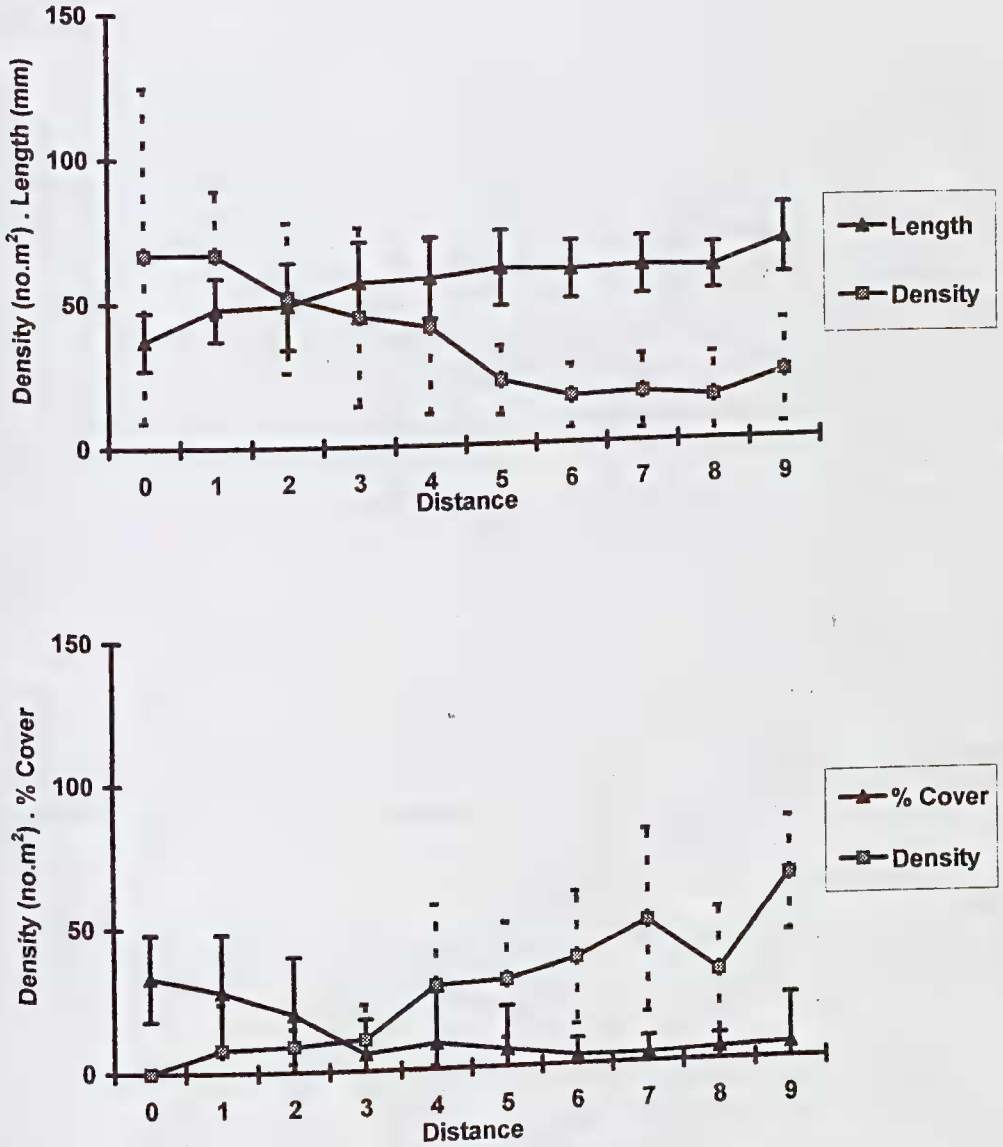

Figure 1.   Horizontal changes in mean shell length and density of the abalone *Haliotis roei* (upper) and the density of *Sargassum* and the percentage cover of coralline algae (lower) with increasing distance from the seaward edge of the platform at Triggs. Means 1 S.E. are shown.

Results

Abalone are concentrated at the seaward margin of the platform. During the four years of intensive sampling on the inshore platform a total of 1961 molluscs were identified and counted at Waterman and 117,477 at Trigg, but not a single specimen of *H. roei* was encountered on the inshore platform at either Waterman or Trigg (Table 1). Some abalone were found in the *Sargassum* zone, primarily the portion closest to the adjoining bare zone. However, only 213 abalone (0.3%) were present of the total of 69,848 molluscs counted in the *Sargassum* zone at Trigg. Both the total number of abalone (579) and the percentage (6.7% of 8602 molluscs) were substantially higher in the *Sargassum* zone at Waterman. This may be a result of individuals forced by the high abalone density in the bare zone to move into adjacent suboptimal habitats. The greatest number of abalone at both Waterman (3763) and Trigg (819) were in the bare zone at the seaward margin of the platform, where they comprised the greatest percentage of total molluscs (21.4 and 4.2% respectively).

Figure 1 shows the density of *H. roei* decreased rapidly with increasing distance from the seaward edge of the platform at Trigg. Maximum densities of 66 m^{-2} occurred at the seaward margin and declined to a consistent level of 17 to 24 m^{-2} on the inshore stations. Mean size of *H. roei* was lowest (36 mm) at the seaward margin and increased gradually to 69 mm at 9 m from the seaward edge.

Linear regressions of abalone density and mean size against percent cover of coralline algae and density of macroalgae showed that density of *H. roei* was correlated with percentage cover of coralline algae (r= 0.52, p<0.001) and conversely with macroalgal density (r= -0.39, p<0.01). Mean size of abalone was also conversely correlated with percentage cover of coralline algae (r= -0.41, p<0.01). The relationship between mean abalone size and macroalgal density was not significant.

The population density of *H. roei* also changes vertically (Figure 2). Density was greatest (108 m^{-2}) at the top of the cliff and decreased sharply with increasing depth. Mean size increased with increasing depth from 57 mm at the top to 87 mm at the 90–120 cm level. Visual observations in other areas confirm that this is a general pattern, with H. roei being most abundant in wave-swept areas near the ocean surface.

A total of 762 *H. roei* were collected from an isolated rock in the Waterman reserve in March 1983 (Figure 3; Table 2). The size frequency histogram was strongly skewed towards larger individuals;
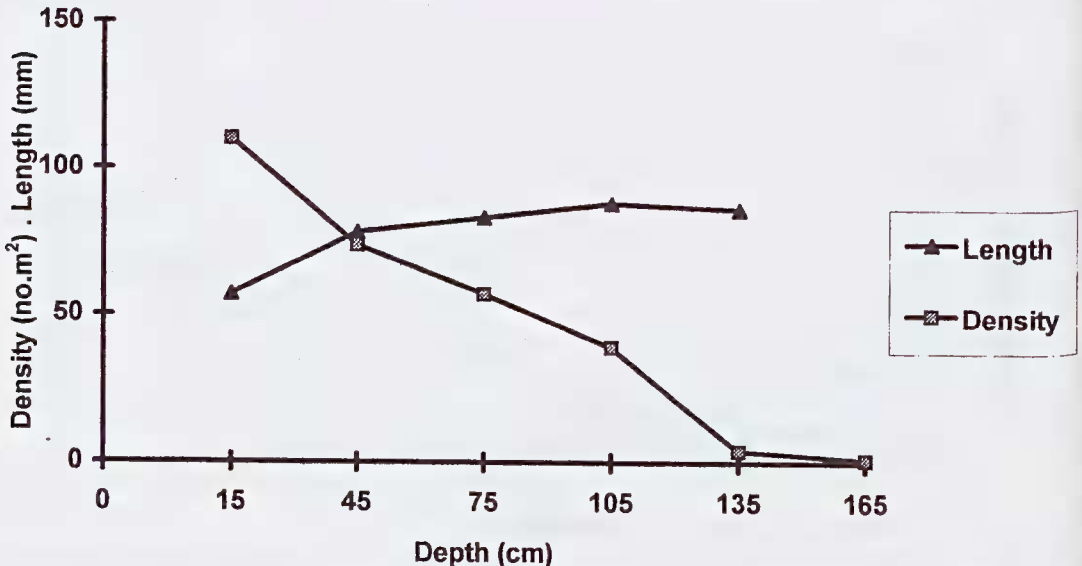

Figure 2.   Vertical changes in density and mean size of the abalone *Haliotis roei* with increasing depth on the seaward vertical cliff at Waterman. Means 1 S.E. are shown.

Table 1.   Total numbers and density of abalone (*Haliotis roei*) in censuses conducted on intertidal rock platforms at Waterman and Triggs annually in January 1983 to 1986.

| | Waterman | | | | | | | |
| | 1983 | | 1984 | | 1985 | | 1986 | |
	No.	Density (no.m⁻²)	No.	Density (no.m⁻²)	No.	Density (no.m⁻²)	No.	Density (no.m⁻²)
Inshore platform	0	0.0	0	0.0	0	0.0	0	0.0
Sargassum zone	387	48.4	149	18.6	12	1.5	31	3.9
Bare zone	1000	125.0	830	103.7	917	114.6	1016	127.0
	Trigg							
	1983		1984		1985		1986	
	No.	Density (no.m⁻²)	No.	Density (no.m⁻²)	No.	Density (no.m⁻²)	No.	Density (no.m⁻²)
Inshore platform	0	0.0	0	0.0	0	0.0	0	0.0
Sargassum zone	77	9.6	41	5.1	34	4.3	61	7.6
Bare zone	123	15.4	178	22.3	249	31.1	269	33.6

537 animals, or 70.5% were in the 2+ age group, and most were probably several years old. Only 17.0% of the population was in the 0+ age class and 12.5% in the 1+ age class. Collecting was done every morning for five days to ensure small individuals were sampled. As the large individuals were removed, vacated spaces were occupied on subsequent days by small individuals which were then easily collected. Because of the intensive collection by two divers over a number of days, we believe the low representation of 0+ and 1+ individuals was real and not a collecting artefact.

The rock was visited at irregular intervals for the next two years. During late summer, when the clearing was undertaken, the rock was separated from an adjoining larger rock by sand. Sand between the rocks was scoured out by wave action during winter and a bare limestone base exposed, allowing mature abalone to migrate from the high densities of the unsampled rock to the cleared sample rock. Thus when the sample rock was cleared again in 1985 and 1987 adult abalone were present. Young abalone could have migrated in either direction. Since they are much less dense and are less mobile than adults the migration is thought to have been slight. In March 1985 a total of 294 *H. roei* were removed from the rock; only 141 were less than 2 years old. In March 1987 151 animals were in this age category. Thus, 0+ and 1+ age classes were sampled for a total of 6 years and a total of 516 animals collected. The 0+ and 1+ year classes averaged only 11.2% of the total original population. At this rate the population would replace itself in 9 years if natural mortality of 2+ animals was zero.

Table 2.   Age and size structure of *Haliotis roei* collected on a small rock at Waterman. Determination of ages is based on growth rates provided by Keesing and Wells (1989). Percentages are of the original (1983) total density.

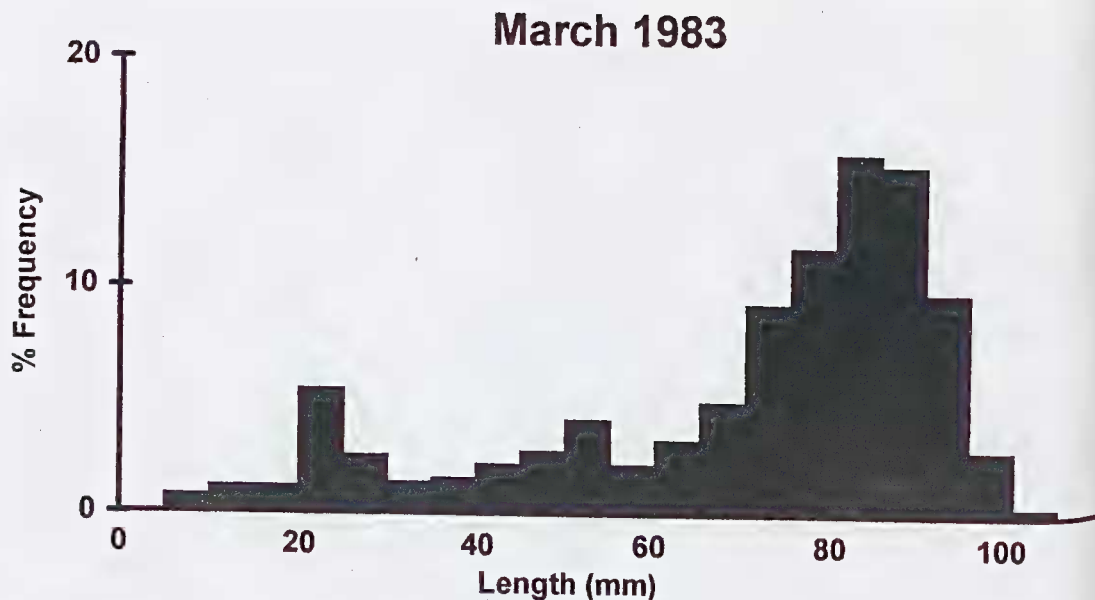| Age (years) | Size (mm) | 1983 | | 1985 | | 1987 | |
		No.	%	No.	%	No.	%
0+	<45	129	17.0	90	11.8	83	10.9
1+	45–65	95	12.5	51	6.7	68	8.9
2+	>65	537	70.5	153	20.1	142	18.5
Totals		761	100.0	294	38.6	293	38.5

March 1983

Figure 3.   Size frequency characteristics of *Haliotis roei* collected on an isolated rock at Waterman in March 1983.

The three sites, two at Trigg and one at Waterman, with the most complete records for the quarterly size frequency measurements are shown on Figure 4; results obtained at the two additional sites were similar. The *H. roei* population at Waterman South was dense (usually between 90 and 100 m^{-2}) and largely adult. The minimum recorded was 62.4 m^{-2} in April 1984 and the maximum was 184.2 m^{-2} in January 1985. Densities of animals <20 mm were always less than 8.0 m^{-2}. Total abalone density was substantially lower at both sites at Trigg, as a result of fishing pressure. At Trigg North densities of adults were between 30.6 and 53.0 m^{-2}. Densities of animals <20 mm ranged from 2.9 to 9.5 m^{-2}, except for January 1985 when they were 19.0 m^{-2}. At Trigg West the range was 35.0 to 88.0, with animals <20 mm <10 m^{-2} except for densities of 18.0 m^{-2} in January 1984 and 14.7 m^{-2} in July 1984.

The sites were also visited annually in January from 1983 to 1986 (Figure 5). In all cases densities of animals <20 mm were very low compared to total densities. Total densities at Waterman varied from 95.8 to 184.2 m^{-2}, but animals <20 mm never exceeded 5.6 m^{-2}. Densities were much lower at Trigg, from 21.4 to 61.0 m^{-2}, with densities of animals <20 mm being up to 19.0 m^{-2}.

Adult animals were collected from the subtidal cliff at the seaward margin of the platform from January 1983 to January 1985 and 40 individuals were recovered each from Trigg and Waterman. During this collecting the subtidal cliff was surveyed for small abalone, but no large concentrations were found.

Discussion

There has been intensive study of molluscs on intertidal rock platforms and the fishery biology of *H. roei* in the Perth metropolitan area (Wells and Keesing 1986; 1989; 1990; Wells *et al.* 1989; Keesing and Wells 1989). In the area studied *H. roei* has a very high growth rate, reaching 46 mm SL in the first year, 64 mm SL in the second year, when they are sexually mature, and 71 mm SL in the third. The total lifespan is not known. Growth rates are substantially higher on the subtidal cliff than on the nearby intertidal platform (Keesing and Wells 1989).

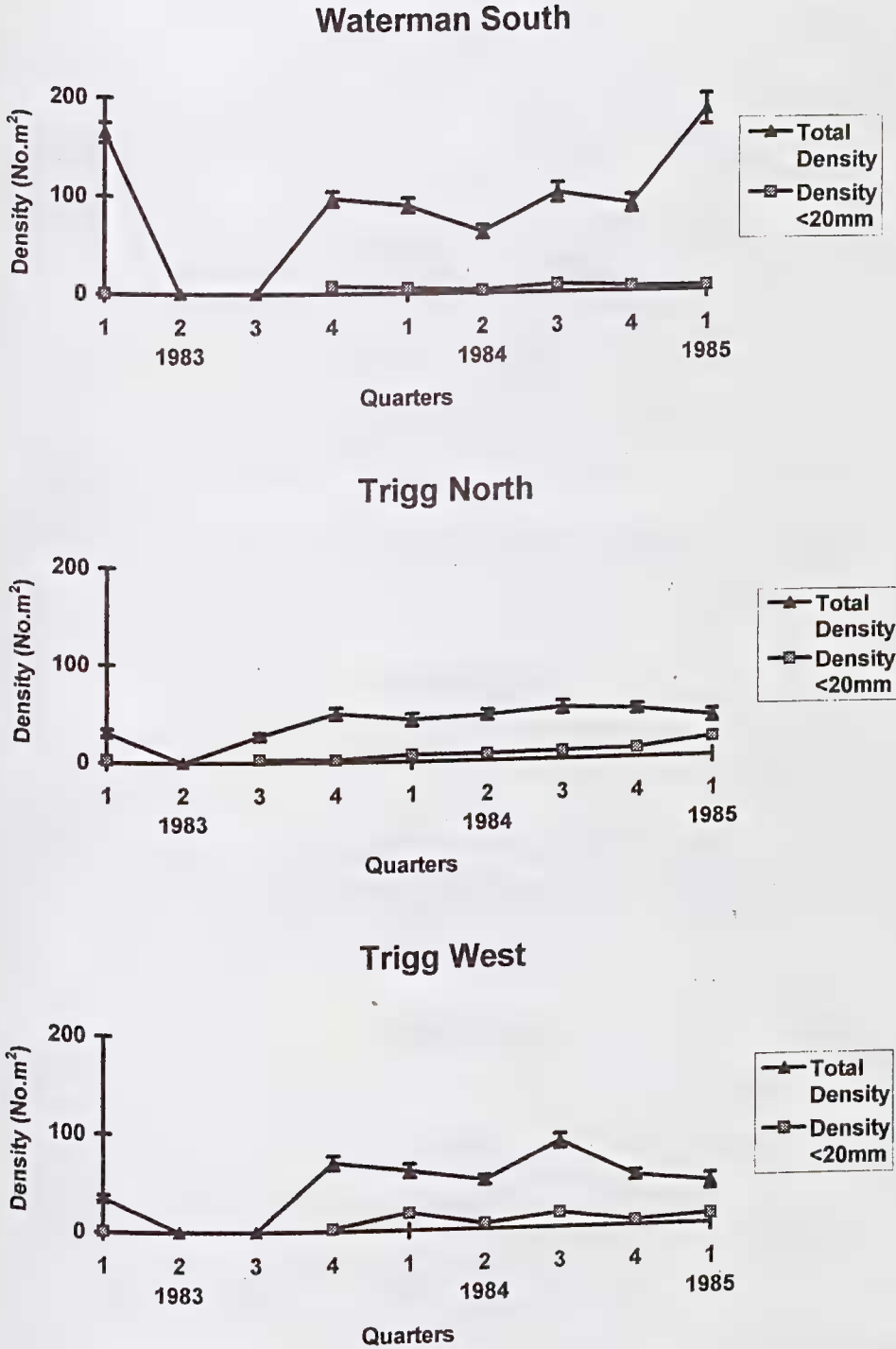## Waterman South

Trigg North

Trigg West

Figure 4. Comparison of total density and density of *Haliotis roei* smaller than 20 mm at three sites on intertidal platforms at Trigg and Waterman at quarterly intervals from January 1983 to January 1985. Means 1 S.E. are shown.
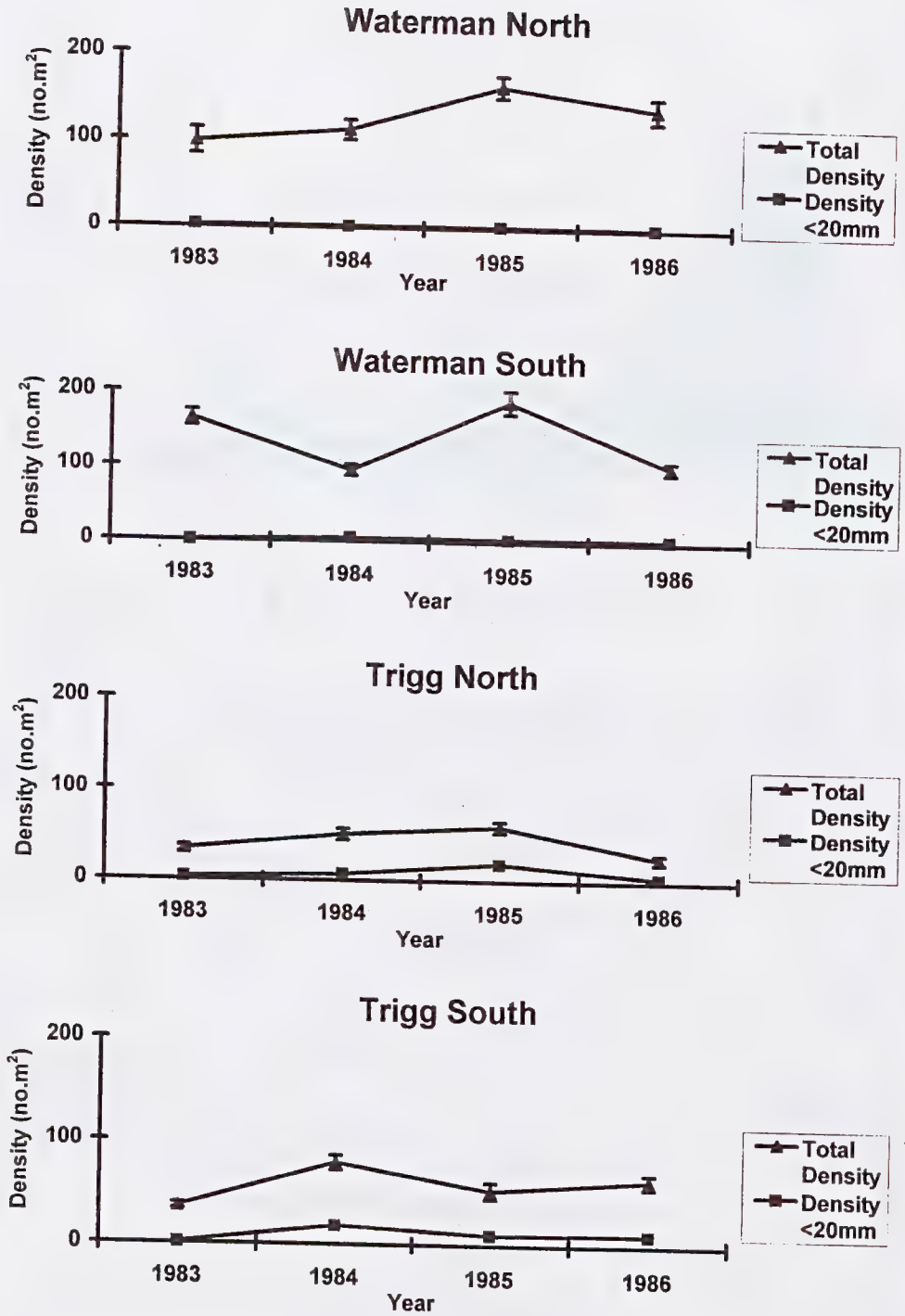
Figure 5.   Comparison of total density and density of *Haliotis roei* smaller than 20 mm at four sites on intertidal platforms at Trigg and Waterman at annual intervals from January 1983 to January 1986. Means 1 S.E. are shown.

When we began sampling in the Waterman reserve in 1983 the population of *Haliotis roei* was maximal with virtually all available sites occupied by adult abalone. Young individuals appeared to be more mobile, suggesting they were occupying suboptimal positions and were moving about regularly in search of a better site. Population density was thus apparently stable. We believed young individuals could recruit only when space became available. In comparison, many vacant spaces were present on the rock platform at Trigg, which was under considerable fishing pressure. Despite the vacant habitats, quarterly and annual data show little difference in the levels of small individuals on the two platforms.

We propose the following life history strategy for *Haliotis roei*: juveniles grow fast, reach adult size quickly, and survive for a number of years as adults. Recruitment of juveniles to the adult population is low, either through a steady annual maturation of juveniles or by substantial recruitment during an occasional good year which sustains the adult population through a number of years when recruitment is very low. If this scenario is true, the lack of juveniles in the population will make *H. roei* particularly susceptible to growth overfishing and potentially recruitment overfishing.

Although recruitment for *H. roei* has been shown to be low, the rapid growth rate allows juveniles to become adults within two years. The relatively short juvenile phase reduces juvenile mortality, and allows the maintenance of substantial adult populations as shown during the rock clearing experiment.

McShane (1995) has examined in detail the literature on recruitment various species of abalone and concluded differences in recruitment can be large. Recruitment is low in species such as *H. laevigata* and *H. iris*, but is high in *H. rubra* and *H. discus hannai*. It is interesting that Shepherd (1990) demonstrated recruitment failure in an unfished population of *H. laevigata*. These studies indicate the substantial need for further data on the life history strategies of other species of abalone.

Acknowledgments

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